SPATIAL DISTRIBUTION OF VISIBLE DESERT SALTS IN THE MCMURDO REGION, ANTARCTICA

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Abstract

Desert environments are distinctive in that they are the only landscapes that accumulate salts in measureable quantities. The McMurdo Dry Valleys in Antarctica are classified as a polar desert, as they maintain very low relative humidities by the sweeping katabatic winds that descend upon the continent and produce very little (<3cm annual) precipitation. Salts are abundant and a notable feature of the soils. Surficial salt crusts were sampled in the top 2 cm of soils in the Dry Valleys and on Ross Island in the area surrounding McMurdo Station to determine their source for formation, as well as to identify spatial trends in the data. Unlike previous salt studies, this one focuses on visible, surface salt crusts with soil depth possibly through sequential evaporation of groundwater as it moves to the surface. Using structural and textural criteria, 2 types of salt crusts may be distinguished: (1) widespread surface crusts with little structure; and (2) thicker salt crusts with amorphous shape that form near boulders. Subsurface soluble salts and stratified salt crusts were not sampled in this study. Chemical analysis of the major ions indicates conflicting trends in major marine ions, suggesting that the marine influence in salt formation is not as significant as was hypothesized. Sodium is the major cation, averaging 70-90% of all major cations measured. Chloride and sulfate are the major anions in the salts, with chloride being the most abundant (<70%) in Taylor Valley surface salts, though it is less abundant at McMurdo station. Higher elevation coastal areas have abundant calcium, up to 60 meq/kg sediment sampled. Statistical analysis reveals that salt chemistries are not significantly different with respect to their sampling elevation, location, and proximity to a water source. Qualitative comparisons of salt chemistries show an influence of formation "type," as salts accumulated under large particle faces are chemically distinct from those that were found alongside streambeds.

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1. Introduction

Deserts make up roughly one-third of the world's landmass. Because of their dryness, the formation of simple salts is a primary process, providing an environment for studying salts, as they are both widespread and measurable. The combination of low precipitation and low relative humidity leads to the precipitation of soluble, binary salts with SO_4^{2-}, Cl^-, and even NO_3^- as the anion in desert soils (ch 7, Goudie and Pye). A great deal of research and investigation has been undertaken on desert soils to describe the salts that are present as well as the combination of geochemical and hydrological processes that form them, in notable deserts like the Great Victoria Desert of Australia, the Namib in Africa, and Atacama in Chile (Rech *et al.*, 2006, Watson, 1985). Much less research on salt accumulations has been done in the soils of polar deserts. The McMurdo Dry Valleys (MCM) are the largest ice-free area (4800 km^2) in Antarctica, and are classified as polar deserts because of their low mean annual temperature and extremely low precipitation. Net precipitation is now thought to be ~3cm wequ yr^{-1} and much of this is rapidly sublimated (Fountain *et al.*, 2010), with little recharge into the soils. The salts are produced from the evaporating soil moisture and are preserved in the McMurdo region because of low precipitation rapid evaporation of melt water, and hence lack of any overland flow. This study seeks to build on two earlier studies conducted in the late 1970s (Claridge and Campbell, 1977, Keys and Williams, 1981) to describe the distribution of salts as well as the key variables that explain their distribution.

2. Site Description

The McMurdo Dry Valleys comprise a mosaic of soils, glaciers, ephemeral streams, ice-covered lakes, and exposed bedrock (Fountain *et al.*, 1999). For a few weeks in the austral

summer, water flows from the glaciers through defined channels and deltas on its way to the lakes. The majority of lakes in the McMurdo Dry Valleys are closed-basin ones with no outflows, with the exception of Lake Miers. This glacial melt is the primary source of liquid water to the lakes and streams (Fountain *et al.*, 1999). In addition to streams, areas of saturated sediment and saline "wet patches" (Levy *et al.*, 2012) exist in isolated locations throughout the valleys. In this project, I describe the various environments in which salt precipitation is common, and I document the geochemistry of the samples and use statistical analysis to determine the potential sources of salt and their effects on local and regional environments.

In 1993, the National Science Foundation established the McMurdo Dry Valleys as a Long-Term Ecological Research Site (MCM-LTER) so that its environment can be extensively studied by scientists in various disciplines to monitor changes in the valleys brought urgent by climate change (<http://www.mcmlter.org>). Hygroscopic salts in the Dry Valleys are preferentially formed in locations where liquid water is present in the austral summer. These include streams or shallow groundwater tracks, and are influenced by the path, flow and subsequent evaporation of liquid water. In MCM, the glacially derived meltwater streams flow between 6-12 weeks per year through permanent channels to the lakes (McKnight *et al.*, 1999). These streams often have salt crusts on the landward edges of the streams on the wetted margins surrounding the streambed where water is exchanged through the nearby sediments in hyporheic zones. In this research project, salts were collected in Miers, Garwood, and Taylor Valley (TV) in close proximity to the lakes, glaciers, and streams.

McMurdo Station, the major U.S. base in Antarctica, is located on Ross Island (figure 1). The McMurdo Station region offers a relatively disturbed setting for comparing salt analyses, as it hosts around 1000 scientists and contractors during the austral summer every year. Salts are

abundant around the station, and sampling was conducted in "town" throughout the austral summer. Ross Island is volcanic and offers a more compositionally homogeneous geologic landscape compared to the Dry Valleys, which contain glacial tills of various lithologies in addition to metamorphic, sedimentary, and igneous bedrock. Salts were sampled between McMurdo station and Castle Rock, Observation Hill, and Hut Point, allowing for the sample collection of salts of varying proximity to Ross Sea and the Ross Ice Shelf. In contrast to salts collected in the Dry Valleys, many of the Ross Island salts were not located in close proximity to a water source. Salts collected around McMurdo Station vary in elevation, distance from the ocean, amount of foot traffic and human activity nearby.

3. Previous Regional Research

The high sublimation and evaporation rates (Gooseff *et al.*, 2006) in the region results in desiccation of the soil, making the soils very dry and susceptible to geochemical alterations with the small additions of water in the form of the "wicking" of water at stream edges, the melting permafrost, exposure of ground water tracks, or "wet patches" (Levy *et al.,* 2012). Though the MCM region is arid, when the atmospheric vapor pressure reaches a critical relative humidity (Leitai *et al.*, 2006), salts will deliquesce to form a saturated brine from the water vapor contained in the atmosphere. In the MCM region, low relative humidity (≤45%) katabatic winds from the west descend from the polar plateau onto the valleys to converge with high relative humidity (75%) marine-generated winds from the east, (Bull, 1966; Marchant and Denton, 1996) creating a geochemical environment conducive to salt precipitation and preservation. The relative humidity affects the solubility and mobility of ions, as warmer air can hold more moisture. When it descends as it cools, its relative humidity increases and can cause salts to deliquesce.

Within the Dry Valleys, three zones have been identified (coastal, intermediate, far – western) to reflect the varying precipitation, wind direction, relative humidity, temperature, and soil-moisture content in the region (Marchant and Denton, 1996). In addition to variations in physical parameters, the zones contain sediment of different lithology and age. In the current study, most salts were collected within the coastal zone, as defined by Marchant and Denton (1996). This zone contains the youngest collection of landforms in the Dry Valleys. Landscape age and evolution can also be important factors in salt formation because they influence the relative contribution of chemical weathering and produce salts with a higher magnesium, calcium, and carbonate content, relative to Na, Cl and SO_4, which are thought to be more atmospherically derived (Keys and Williams, 1981).

Only one detailed investigation has been conducted to understand the distribution and sources of salts in the soils of the McMurdo region. The research conducted by Keys and Williams in 1981 constitutes the largest salt analysis to date in the McMurdo Dry Valleys area, and ten major widespread salts were identified. These are thenardite (Na_2SO_4), gypsum ($CaSO_42H_2O$), halite (NaCl), calcite ($CaCO_3$), darapskite ($Na_3NO_3SO_4H_2O$), soda nitre ($NaNO_3$), mirabilite ($Na_2SO_410H_2O$), bloedite ($Na_2Mg(SO_4)_24H_2O$), epsomite ($MgSO_47H_2O$), and hexahydrite ($MgSO_46H_2O$). These salts were determined through x-ray diffraction analysis. The authors hypothesized that the salts predominantly originated either from marine source or chemical weathering of local rock material.

Major ion analyses revealed a correlation between concentrations of the major ions and distance from the coast (Keys and Williams, 1981, figure 2). Both Claridge and Campbell (1977) and Keys and Williams (1981) found that the SO_4/Cl and NO_3/Cl ratios increase with distance from the coast, which was attributed to the lessoning marine influence inland. The origin of

nitrate salts in the Dry Valley soils was studied (Claridge and Campbell, 1968) because its abundance is rare elsewhere in the world. Sources of nitrogen were speculated to include fixation by ionization processes in the upper atmosphere (Wilson, 1979), and transfer of nitrogenous biological materials in the upper layer to the ocean to the atmosphere during strong wind events (Claridge and Campbell, 1968). Nitrate salts in the Dry Valleys have been attributed exclusively to the sublimation of wind blown snow (Claridge and Campbell, 1968). More recent research has indicated nitrate that is stratospheric in origin and results from NO_x oxidation in the atmosphere (Michalski *et al.,* 2005).

While these salts have been hypothesized to form through weathering and precipitation of marine aerosols, work by Bowser *et al.* (1970) showed that mirabilite ($Na_2SO_4 \cdot 10H_2O$) is common in the coastal areas of the Dry Valleys, and is probably formed by the freezing of seawater. At previous oceanic high stands or at times when the advanced West Antarctic Ice Sheet "pushed" seawater into the valley, Garwood Valley in particular has recorded the extent of the marine high in the form of mirabilite deposits.

Finally, salts are important for potentially contributing nutrients important to sustaining ecosystems (Treonis and Wall, 2005), since they release ions into the environment when they are solubilized. This is particularly true for nitrate salts (Barrett *et al.,* 2007). Understanding the location and chemical composition of visible salts provides important insights in the formation of desert salts, variations in atmospheric chemical input, the possible influence of water sources (including melting permafrost in the austral summer, stream input, hyporheic zone interactions), marine legacy effects, and *in situ* changes regarding relative solubilities of major salts and chemical weathering.

4. Research Goals and Objectives

At noted above, this spatial survey of visible salts builds on previous work to determine the underlying processes of salt formation in the Dry Valley region of Antarctica. This project seeks to determine what visible salts exist in the McMurdo environments and how they are distributed geographically (figure 3). Types of salt environments and their associated chemistries are compared to their location with the objective of determining the fundamental processes that support salt precipitation. Two hypotheses were formulated to evaluate the relative influence of marine aerosols and weathering of soils in salt formation. H1: Salts closer to the Ross Sea should show a marine aerosol influence with higher sodium, sulfate, and chloride content. H2: If chemical weathering is a fundamental process in contributing ions to salt formation, salts on Ross Island will contain more calcium and bicarbonate.

5. Methodology

5.1. Sampling Strategy and Collection

Salts were collected on Ross Island and in the McMurdo Dry Valleys, which are located at ~77˚S and ~78˚S respectively. Sampling sites were selected based on the known availability of salt crusts around these two locations. Samples were collected to reflect the variability of landscapes in Antarctica such that they differ in distance from the ocean, elevation, proximity to streams and lakes, and amount of foot traffic. Access to salt sites in the Dry Valleys was limited by transportation availability and remoteness of location. The valleys sampled in this study include Miers, Taylor, and Garwood Valley (figures 4,5,6). Qualitative field notes and photos were taken at each sampling and date, time, latitude, and longitudinal coordinates were noted.

Sampling took place in January and February 2013. The top 2cm of each salt crust was collected with a plastic scoop and placed into a 2oz Whirl-Pak™ bag to be stored at Crary Lab in McMurdo Station at room temperature until analysis. By the conclusion of the 2012-2013 field season, twenty-four salt samples were collected and weighed on an analytical scale at Crary Lab in McMurdo Station. Eighteen samples from the 2011-2012 season that were collected by Andrew Fountain and Michael Poole were added for a total of forty-two samples.

5.2. Salt Extraction Experiment

In February 2013, approximately 10g of sediment containing salt crusts were weighed and placed into a liter of 18.2 mega-ohm deionized water, where they were stirred and let to sit for 30 minutes at room temperature (~20C). Earlier analyses determined that the dissolved ion concentrations did not significantly change after 30 minutes in solution (Welch, KA, personal communication). The solutions were extracted using a 5mL Gilson Pipetman™ and placed in plastic tubes for ion chromatography analysis of major cations and anions in Crary Lab. The remaining sediment from each site was frozen and sent back to Byrd Polar Research Center at The Ohio State University where it could be used for further chemical analyses.

5.3. Major Ion Analysis

Major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, F^-, NO_3^-, SO_4^{2-}, PO_4^{3-}) were analyzed by a Dionex DX-120 ion chromatograph (IC) with an AS40 automated autosampler as originally described by Welch *et al.* (2010). At the beginning of each run, seven incrementally increasing standards were measured to construct a calibration curve from which sample concentrations were later calculated. Every ten samples a verification standard and duplicate standard were analyzed to determine precision while accounting for any instrument drift. Alkalinity (HCO_3^-) was calculated through charge balance according to the following:

$$HCO_3^- = \sum \text{cations (meq/kg sediment)} - \sum \text{anions (meq/kg sediment)}$$

The average error between calculated and measured alkalinity values in over 900 Dry Valley stream samples from multiple summer seasons has been calculated to be ±14%, and this is the best estimate for the precision of alkalinity determined from this charge balance method (Lyons *et al.*, 2012). Data (table 1) show results from the IC analysis, and precision is shown (table 2) for the measured ions analyzed via IC.

6. Results

Ion chromatography data were normalized to percent milli-equivalents per kilogram of soil and plotted in ternary diagrams (figures 7 and 8) to show the relative contributions of the major ions in the salt crusts. GPS coordinates of samples were taken so that the distance to the ocean could be determined in order to evaluate to show the marine influence on salt composition. The ternary diagrams, a table summarizing the concentrations of detectable ions, and other associated figures are shown in the appendix. In addition to graphic interpretation, a t-test was conducted to determine if the specific locations where salts were taken were statistically different with respect to their chemistries at the p=.05 level. The results are summarized in tables 3 and 4.

7. Discussion

7.1. Anion & Cation Analysis

After Marchant and Denton (1996), the data were grouped according to their spatial area of interest (AOI). The AOIs include the surrounding McMurdo Region within Ross Island

("McMurdo Remote"), Lake Fryxell Basin, Lake Hoare Basin, Lake Bonney Basin, Garwood Valley, and Miers Valley.

Several trends consistent with the earlier studies (Keys and Williams, 1981; Claridge and Campbell, 1968) have been identified among the AOIs. The plot of SO_4^{2-}, Cl^-, and alkalinity (HCO_3^-) shows a distinction between the SO_4^{2-} content of Dry Valley samples and those from Ross Island. The widespread presence of Cl^- and SO_4^{2-} in salts, ranging from 4 to 10,000 meq/kg sediment, is indicative of a marine origin (Keys and Williams, 1981). However, the graph of SO_4/Cl vs distance from the sea (figure 9) shows a bimodal distribution with no middle members, indicating two extremes in the geochemistry of the salts. Thenardite (Na_2SO_4) was found to be concentrated in the eastern and western parts of Taylor Valley by Nishiyama and Nakai (1975), which could explain the high concentration of both sodium and sulfate. Furthermore, all salts are enriched in sodium relative to seawater, suggesting that marine aerosols alone cannot account for the chemical composition of the salts. The plot of chloride shows no correlation in chloride concentration with distance from the coast in the salts sampled (figure 10). Furthermore, they all plot above the halite ratio of sodium to chloride, suggesting that halite isn't the only sodium salt in the soils (figure 11). Alkalinity (HCO_3^-) concentrations in the samples vary but the samples from the McMurdo region are constrained fairly well. Keys and Williams (1981) attributed the presence of bicarbonate to the biological activity in the eastern Taylor Valley, but excess bicarbonate can also be a product of aluminosilicate weathering or remineralization of organic material. In this study, the alkalinity high-end members are from areas in close proximity to a water source in the eastern Dry Valleys, which could sustain microbiological organisms or produce HCO_3^- through weathering processes (Gooseff *et al.*, 2002; Treonis and Wall, 2005). Most of the samples contain little nitrate, which is consistent with Keys and Williams (1981).

Additionally, nitrate salts can accumulate in soils over time if there is no liquid water to solubolize them, as has also occurred in northern Chile and in higher elevations in the TransAntarctic Mountains where liquid water is lacking (Claridge and Campbell, 1968). In this study, the anomalously high nitrate sample is from the summit of Observation Hill, an area of higher elevation than the other samples in the AOI. McMurdo is a very young landscape and has been anthropogenically manipulated by human activity, whereas the Dry Valleys represent older landscapes and have the potential for the accumulation of NO_3.

The anion ternary plot shows the variability in all of the grouped salts, indicating that Cl^- isn't the major anion, as was hypothesized if the marine influence is large. Garwood salts which are probably mirabilite (formed by the freezing of seawater) are largely SO_4^{2-}, which was expected based on previous work. However, the variability within Taylor Valley is significant. Adjacent basins do not show similar chemistries of the salts sampled, and none of the salt groups look like the average precipitation. The precipitation and salt chemistry contrasts greatly, indicating that atmospheric deposition is not the sole source of ions to the salts. The traditional Piper Diagram is not a very informative way to represent the analyzed cations in this study because Na^+ is by far the major cation constituent in all salts sampled. In order to better assess the differences in salts, data are plotted to show K^+, Ca^{2+}, and Mg^{2+} (figure 12). Within the cation plot, the average precipitation varies largely with the average chemistries by location.

Plots of SO_4/Cl and NO_3/Cl were made to determine if the ratios increase with distance away from the coast. Though weakly correlated, scatter plots of SO_4/Cl and NO_3/Cl show a negative relationship with distance inland. Contrary to the findings of Keys and Williams (1981), the Cl^- concentration does not decrease dramatically in the western areas of the valley. The explanation for this is not immediately clear and is likely rooted in the nature of the salt crust

formation, as many of them formed near saline closed-basin lakes. In addition, these results suggest that Cl^- salts are very abundant in visible salt crusts, independent of location in McMurdo town. Higher SO_4 concentrations are found in McMurdo town, potentially explained by the samples' proximity to Mt Erebus and volcanic sulfate aerosols (IIyinskaya *et al.*, 2010, Nishiyama *et al.,* 1975). Because only visible surface salts were sampled (figure 13), they reflect the sequential nature of evaporation of ground water percolating through the soils (Levy *et al.,* 2011), preferentially precipitating the most soluble salts last at the surface. Therefore, as water moves slowly down gradient the least soluble salts are lost from the water first, thereby creating a "chromatography" effect, as first described by Wilson (1979).

Though XRD analysis was not conducted in this study, qualitative stoichiometric comparisons were made to distinguish the potential salt species present in this study. Graphs reveal that the cations are dominated by sodium in all areas sampled, which is well balanced by chloride, sulfate, and bicarbonate (figure 14). The anions vary spatially, though the bicarbonate contribution in Miers Valley is significant, suggesting that sodium bicarbonate may be present.

7.2. Qualitative field observations and Statistical Analysis

The appearance of each salt crust differs from site to site. In areas adjacent to stream beds, the salts are widespread and occur in tracks up to 5m in length. Isolated salts also occur within McMurdo Station and the Dry Valleys, and are not associated with a body of water in close proximity. Using structural and textural criteria, 2 types of salt crusts may be distinguished: (1) Widespread surface crusts with little structure, and (2) Thicker salt crusts with amorphous shape that form near and underneath boulders. Subsurface soluble salts and stratified salt crusts were not sampled in this study.

A two-sample t-test analysis was conducted to compare the AOIs and their associated chemistries for a significant difference. A t-test is appropriate for the data since each group contains less than thirty sites, and the same treatment was applied to each sample. The average values of each relative elemental percentage for an AOI were used in an analysis to determine significant independence (H_0: The means for the two AOIs compared are equal. H_A: The means for the two AOIs compared are not equal). All of data is not robust (summarized in table 4) but there are identifiable patterns to qualitatively determine differences in salts. Differences in AOI and differences in salt type (isolated, along water, human traffic, high elevation) are reflected in the relative significance of the test. When the calculated t-statistic is more extreme (in the positive or negative direction) than the literature values, the null hypothesis is rejected in favor of its alternate, H_A. Among the tests performed, the significant differences at the $p=.05$ level occur with the McMurdo salts. In McMurdo town, the contribution of sodium is significantly lower than that for the remote samples. The high traffic salts have more magnesium, potassium, and calcium than those remote sites, potentially suggesting a different mechanism for formation, as lower elevation areas have more water, hence more weathering. The most significant differences do not occur between those samples near and far from water as was hypothesized, but rather exist in the samples near town. The more isolated salts contain more Na and Cl, suggesting that the marine influence may apparent, as the widespread salts occur in areas closer to freshwater stream and lake bodies.

7.3. Potential Sources of Bias and Error

This study commenced in 2011 when salts were collected in TV and Garwood Valley by various MCM-LTER participants. Thus, the sampling strategy is not consistent from sample to sample in this more inclusive study. The varied nature of the salt deposits presents a bias when

the data are normalized to milligrams of salt per kilogram of sediment because some of the salt existed as a crust while other salt samples thinly coated the surface area of the sediment. Efforts were taken to reduce these biases by recording the weight of each sample and systematically employing the same technique of sampling for the salts collected in 2013. Data are also represented as ratios to allow for true comparison because simple comparisons by concentration could introduce a bias. Error was reduced by cleaning each liter bucket five times between samples during the salt extractions, while also holding the time of solution constant at 30 minutes.

8. Conclusion

Salts in the McMurdo region reflect the complicated Antarctic landscape, as their chemistries vary spatially but show correlations in chemistry when they are categorized further according to their location. Salts from Garwood Valley have an order of magnitude higher sodium concentration than any other samples, even after accounting for chloride associated with halite. Salts closer to a water source (including fresh water) are higher in chloride than those that are on Ross Island and near the Ross Sea, though the Ross Island salts in McMurdo Town are higher in sulfate. Within McMurdo Station, salts collected in areas of high human activity have significantly more magnesium and chloride compared to "remote" salts (2 meq/kg sediment and 90 meq/kg sediment compared to .6 meq/kg sediment and 16 meq/kg sediment, respectively), that are relatively isolated. Statistical analysis shows differences in the chemistry of high traffic area salts in McMurdo, suggesting that human activity may not be a secondary variable in controlling salt formation. Salts from the 2011-2013 sampling differ from those in the 1970s studies because their NO_3/Cl ratios and SO_4/Cl ratios do not increase with distance away from

the coast, but the all of the samples were taken within the coastal zone, suggesting marine aerosol condensation could be dominant process in controlling salt formation. Plots showing variation in salt chemistries from the average precipitation indicate that salts are not solely the product of marine aerosol deposition. Qualitative stoiciometric analysis shows that sodium is the major cation constituent and it is balanced by chloride, sulfate, and bicarbonate, reflecting diversity of sodium-rich salts. The Miers Valley sample indicates that sodium bicarbonate may be present, which was not previously identified by Keys and Williams (1981). Because the salt chemistries are different depending on their AOI and type, it is likely that they form from different mechanisms. Since only surface salts were sampled, sequential evaporation is a probable mechanism for preferentially precipitating the most soluble salts at the soil-atmosphere boundary.

9. Recommendations for Future Work

Laboratory analyses were limited in this project due to the condensed timeline of sample collection in January to the project's completion in April. Possible salt mineralogy could not be determined by simple stoichiometric comparisons so further analysis using an x-ray diffraction technique following Keys and Williams (1981) could be used to identify major salt species. Sediment leaching experiments could be conducted to determine the composition of the sediment under the salt crusts, which could potentially help to better explain *in situ* weathering and its contribution in forming salts. Geochemical modeling to better describe the subsurface processes reflecting chemical divides (Drever, 2002; Marion and Kargel, 2007) will give clues to the water evolution. Future collection of salts could be concentrated on areas of high elevation and increasing distance from the coast so that the role of nitrate can be quantified statistically. As salts dissociate and contribute solutes like NO_3 to the water, they could potentially support

nematode life. As the lake levels rise with climate change, increasing the connectivity of hydrodynamic systems in the Dry Valleys, the relationship between solubolized salts and ecological environments will be important. Experiments to study the interactions of salt dissolution and the sustaining of micro-communities could help to understand the seasonal nature of nematode populations. Though it was outside the scope of this project, data from global desert salts could be compiled to allow for a large-scale comparison of composition, possibly revealing differences of evaporation in warm deserts as opposed to freeze drying in polar deserts. Finally, long-term monitoring of the salts could be initiated so that major salt bodies are tracked and measured (GPS, IC analysis) to determine if they are ephemeral or permanent bodies, and to what extent their chemistry varies from season to season.

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Appendix

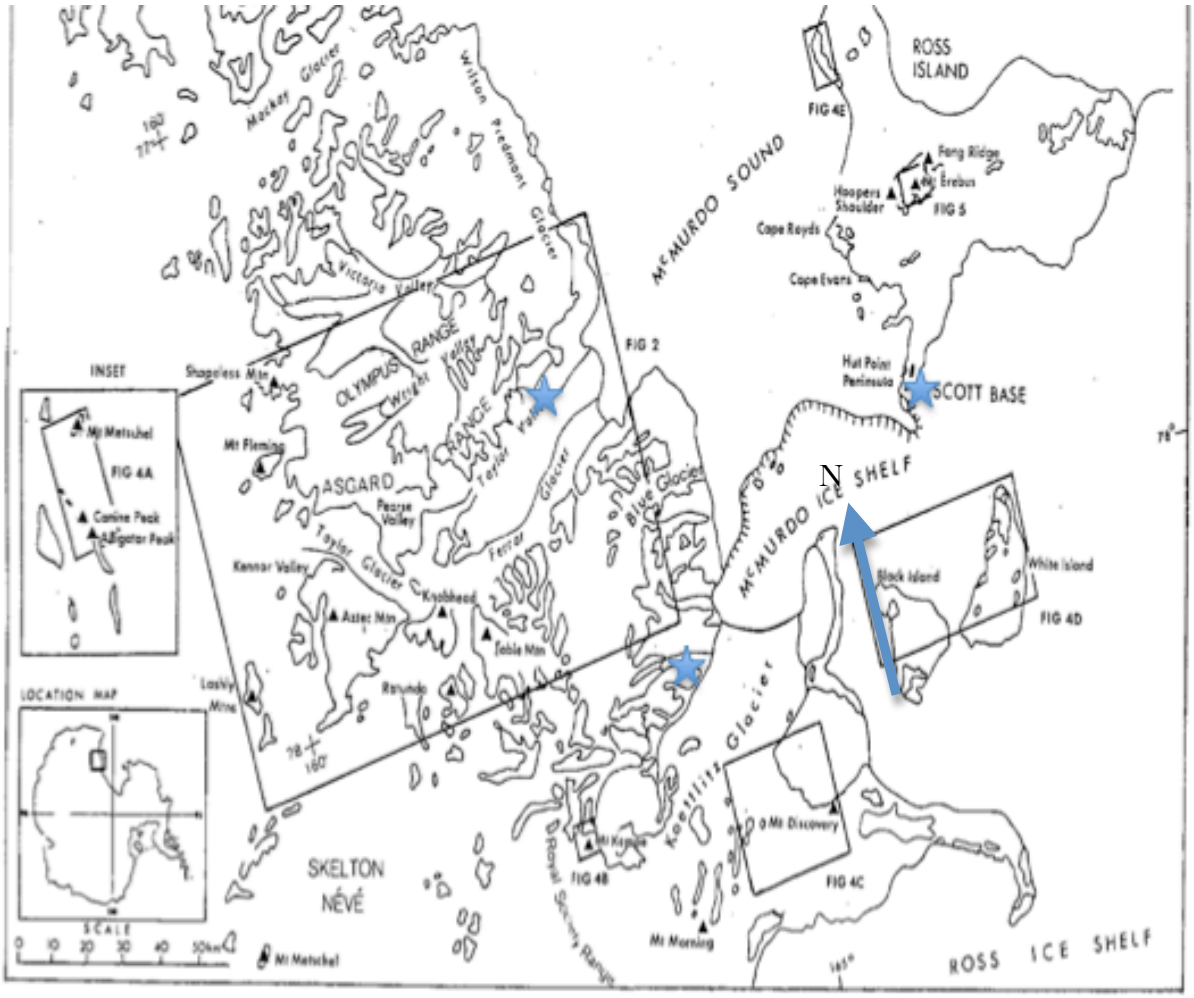

Figure 1. Map of McMurdo Region, showing 3 main sampling sites, from dissertation of Keys (1979), University of Victoria in Wellington

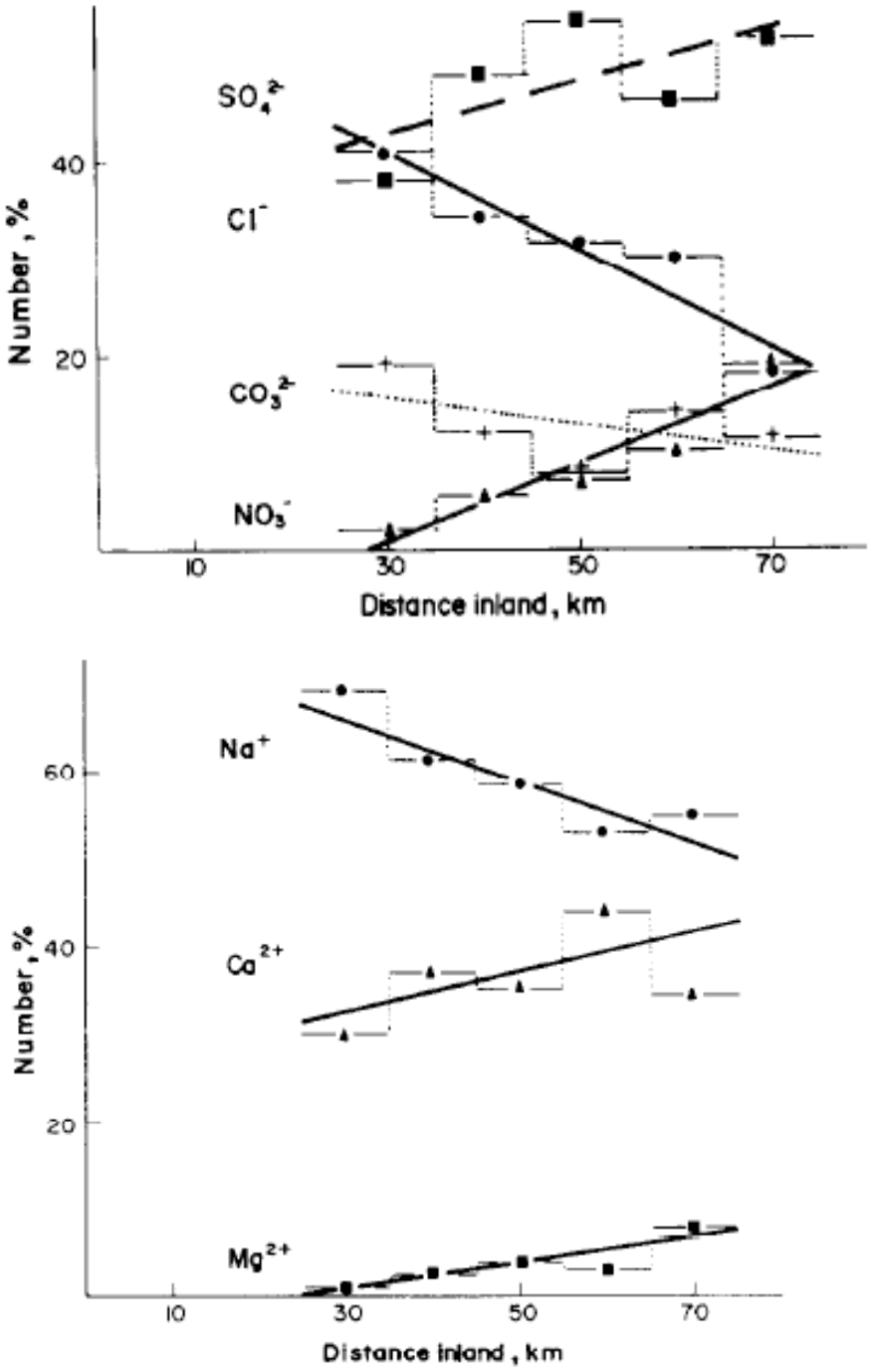

Figure 2. Previous findings by Keys and Williams (1981) show relationship of ion concentration with distance inland.

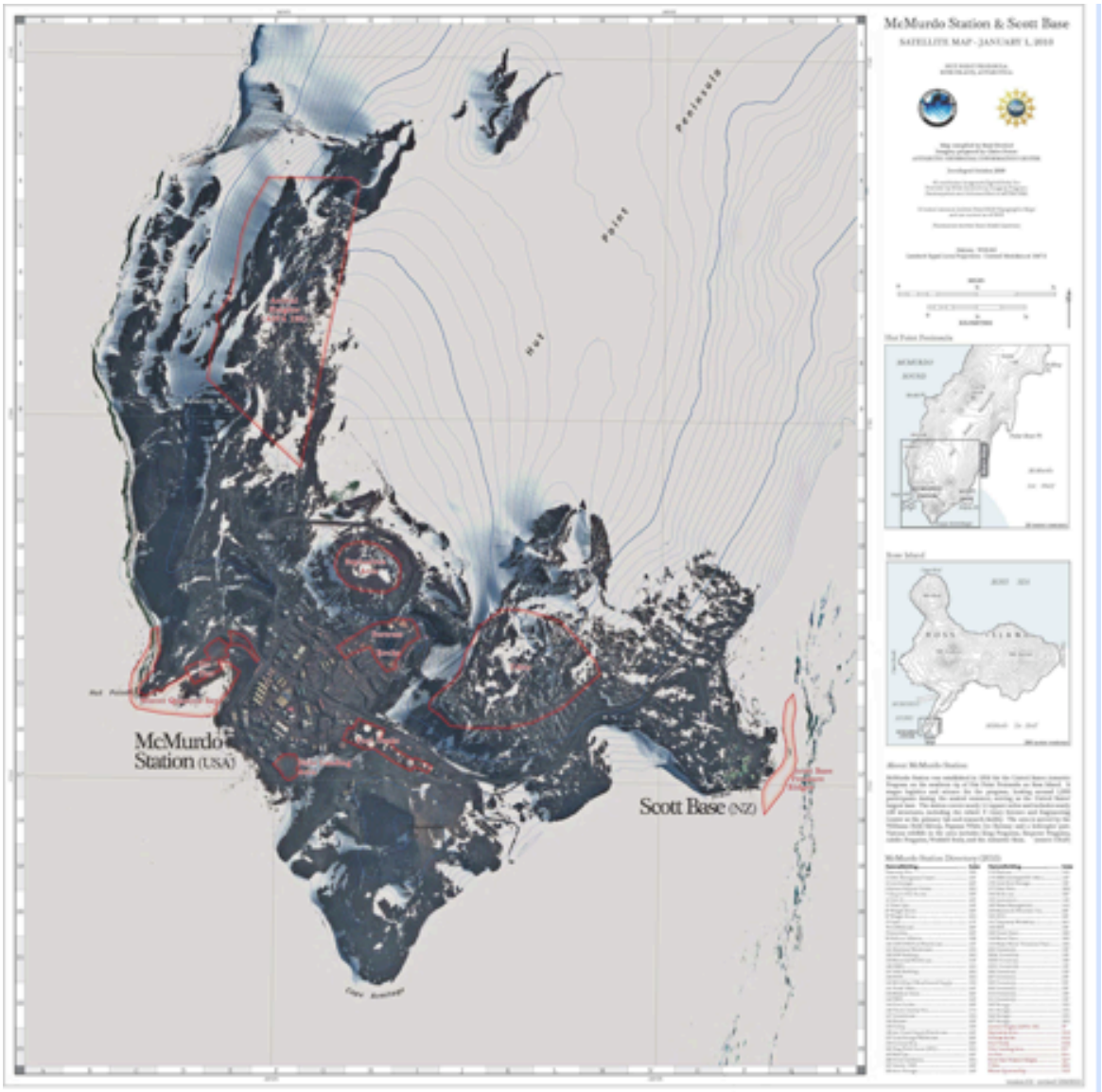

Figure 3. Map of McMurdo Town, where remote and in town sampled were collected.

Figure 4. Map of Miers Valley, where a salt sample was taken 3 m from the lake.

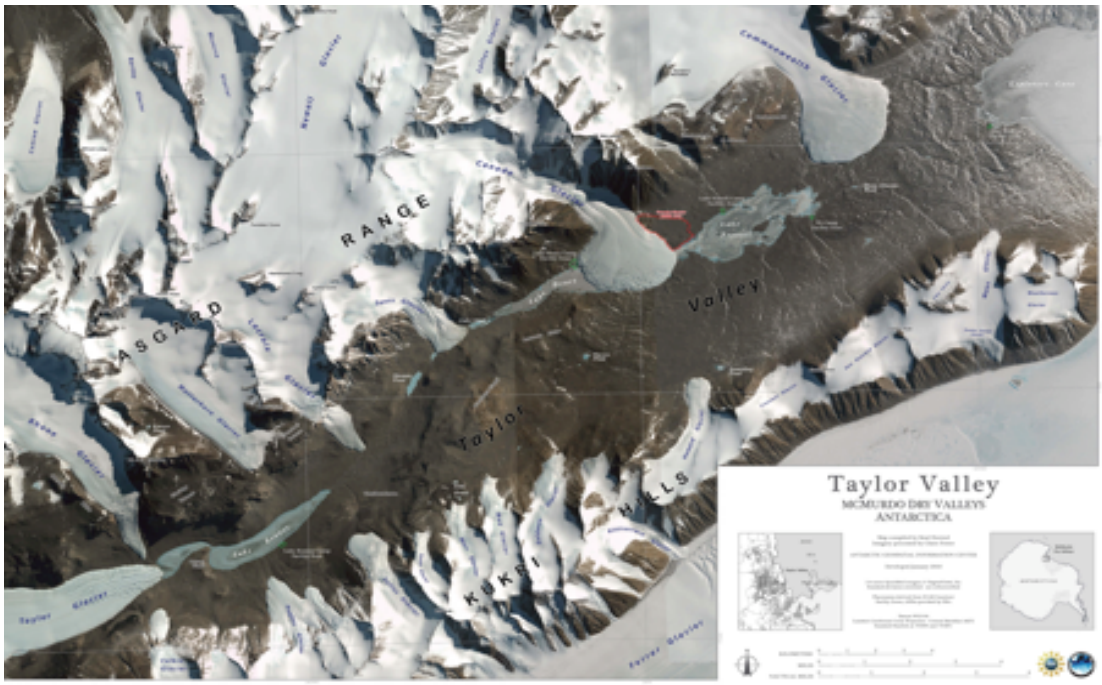

Figure 5. Map of Taylor Valley, where salts were collected in the Fryxell, Hoare, and Bonney Basins.

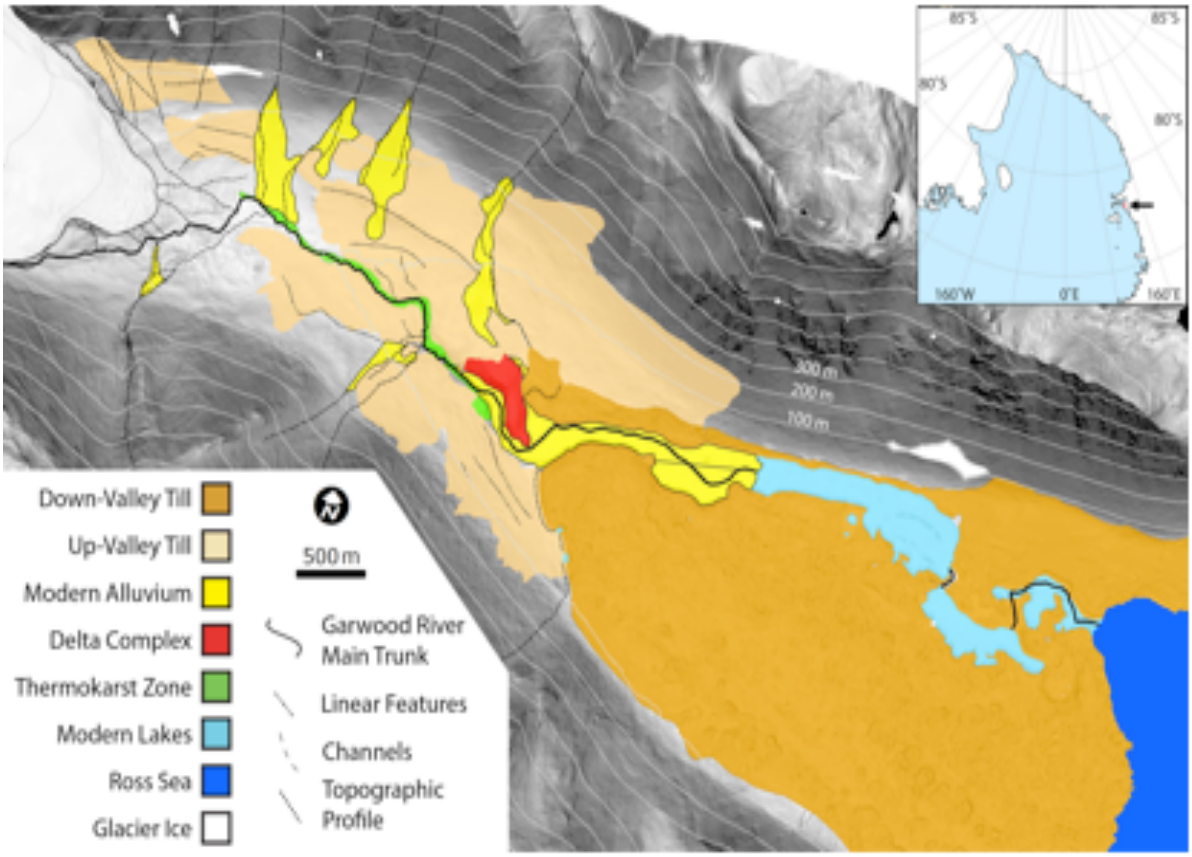

Figure 6. Map of Garwood Valley

Table 1. Ion-chromatography analysis results show relative contribution of ion in meq/kg soil sampled as well as % of total anions or cations

ID #	AOI	Na	K	Mg	Ca	F	Cl	NO3	SO4	HCO3	% Na	% K	% Mg	% Ca	% F	% Cl	% NO3	% SO4	% HCO3
	McMurdo Region																		
1	Building 160 (HF)	56.03	3.02	1.96	2.13	0.35	24.15	0.00	26.71	13.24	88.73	4.79	3.11	3.37	0.54	37.47	0.00	41.44	20.55
2	1/2 OH (HF)	117.46	8.64	2.21	7.34	1.50	12.82	0.70	109.27	12.89	86.59	6.37	1.63	5.41	1.09	9.34	0.51	79.66	9.39
3	Top of OH	16.75	1.81	1.46	2.08	0.46	10.82	2.01	4.98	4.81	75.80	8.18	6.61	9.40	1.97	46.89	8.71	21.57	20.85
4	W of OH near pond	292.41	7.47	1.34	37.87	0.37	17.12	0.83	313.72	8.25	86.24	2.20	0.40	11.17	0.11	5.03	0.24	92.19	2.43
5	Base of OH near Kiwi Base	234.73	5.28	1.54	58.69	0.34	28.23	0.84	248.87	23.40	78.18	1.76	0.51	19.55	0.11	9.36	0.28	82.50	7.76
6	HP Trail Start	353.42	4.55	1.47	5.26	2.38	122.23	1.26	99.27	140.59	96.91	1.25	0.40	1.44	0.65	33.42	0.34	27.14	38.44
7	HP Trail near ASPA	565.20	4.63	13.10	22.05	0.39	68.19	2.84	543.78	0.00	93.42	0.77	2.17	3.65	0.06	11.08	0.46	88.39	0.00
14	Base of OH near cylinders (HF)	612.53	27.47	11.91	38.26	1.07	210.44	6.32	496.21	0.00	88.75	3.98	1.73	5.54	0.15	29.47	0.88	69.49	0.00
15	Outside galley smoker (HF)	154.57	7.45	2.64	15.51	0.24	47.30	1.11	130.07	3.31	85.79	4.13	1.47	8.61	0.13	25.98	0.61	71.45	1.82
16	Troll Bridge (HF)	267.82	16.78	2.98	10.60	1.98	91.24	2.54	171.55	32.95	89.82	5.63	1.00	3.55	0.66	30.39	0.85	57.13	10.97
17	JSOC stairs (HF)	406.20	5.55	3.83	12.19	0.24	100.21	2.24	329.75	0.00	94.96	1.30	0.89	2.85	0.06	23.17	0.52	76.25	0.00
18	Crary Truck Area (HF)	589.95	10.74	4.86	12.19	1.07	200.56	6.07	405.43	8.02	95.50	1.74	0.79	1.97	0.17	32.29	0.98	65.27	1.29
19	Southern Exposure Bridge (HF)	82.21	1.45	1.44	11.29	0.00	15.09	0.27	78.32	3.75	85.29	1.51	1.49	11.71	0.00	15.48	0.28	80.39	3.85
20	Underneath Crary Phase 1	79.40	2.88	2.68	15.04	0.36	13.87	1.64	79.30	6.69	79.40	2.88	2.68	15.04	0.35	13.62	1.61	77.84	6.57
21	Base of Castle Rock West	62.99	1.58	1.05	12.05	0.48	26.61	1.00	39.05	11.29	81.10	2.04	1.35	15.51	0.62	33.93	1.28	49.78	14.39
22	Castle Rock Summit	1.58	0.06		0.56	0.00	0.27	0.00	0.30		71.87	2.59	0.00	25.54	0.00	47.25	0.00	52.75	0.00
23	Hill Near VMF (HF)	464.45	8.58	1.44	13.57	0.44	263.90	0.81	211.84	12.14	95.17	1.76	0.29	2.78	0.09	53.95	0.17	43.31	2.48
27	DORM 208 PIERSIDE (HF)	163.20	9.11	3.50	4.87	0.26	77.63	1.09	103.92	0.14	90.33	5.04	1.94	2.69	0.14	42.41	0.60	56.78	0.07
28	HAMSHACK (HF)	163.47	23.94	0.76	16.64	0.75	68.52	3.72	98.45	34.00	79.82	11.69	0.37	8.12	0.36	33.35	1.81	47.92	16.55
29	JSOC B165 (HF)	235.97	3.36	7.06	10.13	0.20	151.21	2.07	106.03	1.74	91.99	1.31	2.75	3.95	0.08	57.88	0.79	40.58	0.67
30	SIDE OF B175 (HF)	357.32	4.58	3.50	5.68	0.40	9.39	0.11	363.77	0.00	96.29	1.24	0.94	1.53	0.11	2.51	0.03	97.35	0.00
	Garwood Valley																		
41	#10 LOWER GARWOOD	192.63	1.77	2.02	4.04	1.49	68.43	2.62	15.08	114.18	96.09	0.89	1.01	2.02	0.74	33.91	1.30	7.47	56.58
44	GARWOOD VALLEY SALT	7129.50				0.00	0.00	0.00	7125.34		100.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
45	JLS 011412 SALT #2	30.68	0.55	0.00	1.34	0.00	0.85	0.00	31.42	0.33	94.19	1.68	0.01	4.12	0.00	2.61	0.00	96.39	1.01
	Taylor Valley																		
24	Priscu stream 1	0.86	0.23	1.00	0.82	0.15	15.86	0.88	35.71	0.00	29.51	7.78	34.58	28.13	0.28	30.16	1.66	67.90	0.00
25	Priscu stream 2	26.17	0.85	1.84	18.10	0.33	11.57	0.44	26.34	9.62	55.72	1.82	3.93	38.54	0.68	23.95	0.92	54.54	19.91
31	#1 LAKE HOARE	767.03	2.68	7.38	8.01	5.68	167.16	4.04	314.67	298.56	97.70	0.34	0.94	1.02	0.72	21.16	0.51	39.83	37.79
32	#2 LAKE HOARE	43.12	5.03	4.26	6.18	0.42	23.61	0.10	37.16	0.16	73.59	8.59	7.27	10.54	0.68	38.42	0.16	60.48	0.26
33	#3 LAKE HOARE CAMP	52.96	4.41	1.13	7.52	0.00	25.29	0.26	30.33	10.94	80.21	6.68	1.71	11.39	0.00	37.84	0.39	45.39	16.37
34	#4 LAKE HOARE	407.60	27.71	0.21	9.60	0.31	346.60	0.90	47.02	50.49	91.57	6.22	0.05	2.16	0.07	77.83	0.20	10.56	11.34
35	#5 NEW HARBOR	573.10	2.49	13.33	23.75	0.18	24.30	0.00	536.87	60.42	93.54	0.41	2.18	3.88	0.03	3.91	0.00	86.34	9.72
36	#5 NEW HARBOR 2HR SOAK	598.11	2.84	13.89	28.45	0.20	25.29	0.00	563.40	63.91	92.98	0.44	2.16	4.42	0.03	3.87	0.00	86.30	9.79
37	#6 NEW HARBOR	548.65	6.95	6.15	12.51	0.86	405.91	1.71	60.42	109.47	95.54	1.21	1.07	2.18	0.15	70.18	0.30	10.45	18.93
38	#7 NEW HARBOR	277.94	6.32	2.22	18.23	0.69	113.46	0.00	22.88	169.22	91.22	2.07	0.73	5.98	0.23	37.05	0.00	7.47	55.25
39	#8 F6 CAMP	1647.81	24.81	10.51	6.76	3.65	900.95	17.69	248.76	525.83	97.51	1.47	0.62	0.40	0.21	53.09	1.04	14.66	30.99
40	ANDREW #9 F6	169.67	2.13	0.00	3.06	0.34	95.14	0.27	17.67	61.45	97.03	1.22	0.00	1.75	0.19	54.41	0.16	10.11	35.14
9	Delta Stream near Hwd	405.92	8.98	1.14	5.31	1.31	277.73	0.83	34.07	108.18	96.34	2.13	0.27	1.26	0.31	65.79	0.20	8.07	25.63
10	Small pond by Hwd	584.81	7.84	1.77	6.81	2.22	304.83	2.05	110.94	182.42	97.27	1.30	0.30	1.13	0.37	50.60	0.34	18.41	30.28
11	Green creek/Canada	499.12	6.69	1.51	5.81	1.96	262.19	7.16	20.63	222.22	97.27	1.30	0.30	1.13	0.38	50.99	1.39	4.01	43.22
12	New mouth of Green	285.73	2.32	0.86	2.72	0.95	191.67	0.14	13.43	86.02	97.98	0.80	0.29	0.93	0.32	65.59	0.05	4.60	29.44
13	Lost Seal	520.14	3.59	1.37	4.33	2.69	283.56	0.57	31.54	211.99	98.25	0.68	0.26	0.82	0.51	53.47	0.11	5.95	39.97
	Miers Valley																		
8	Miers near moat	311.02	9.35	1.28	5.04	1.18	71.53	0.54	43.81	210.51	95.20	2.86	0.39	1.54	0.36	21.84	0.17	13.37	64.27

Table 2. Table showing precision for various ions measured on the IC

Ion	Percent Error
Na	0.11
K	3.01
Mg	0.00
Ca	2.30
F	12.80
Cl	0.00
NO3	3.10
PO4	0.00
SO4	0.08

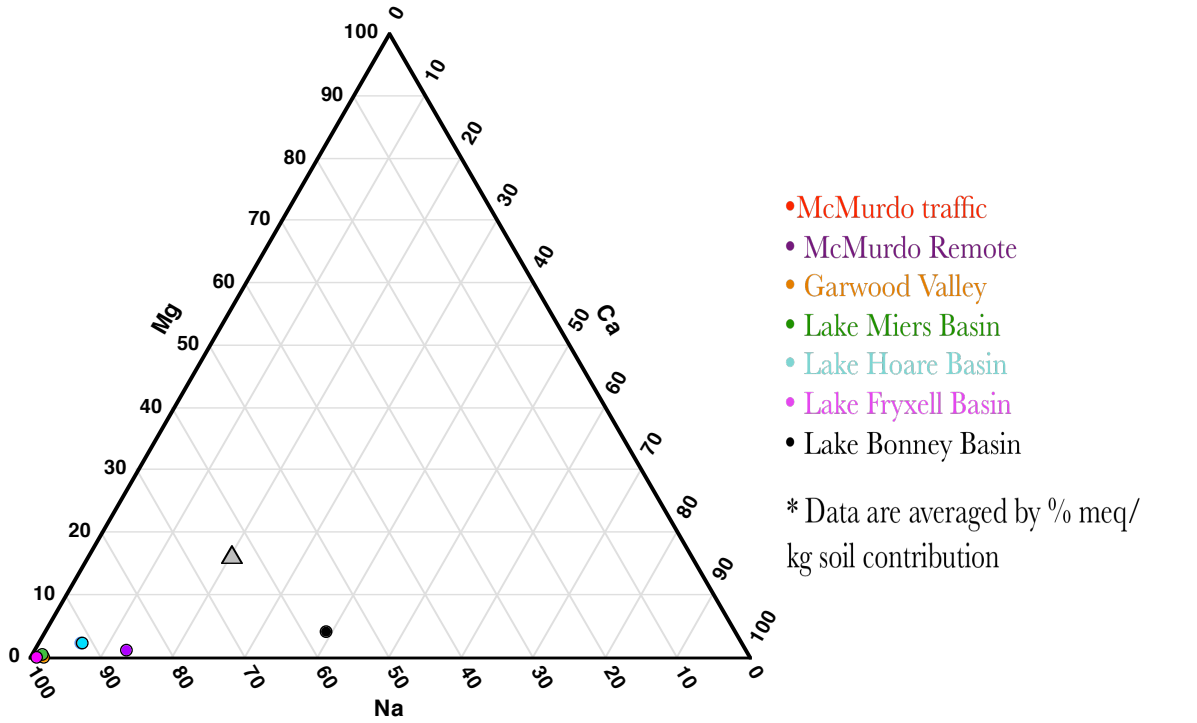

Figure 7. Cation Ternary Diagram with grey triangle representing TV precipitation.

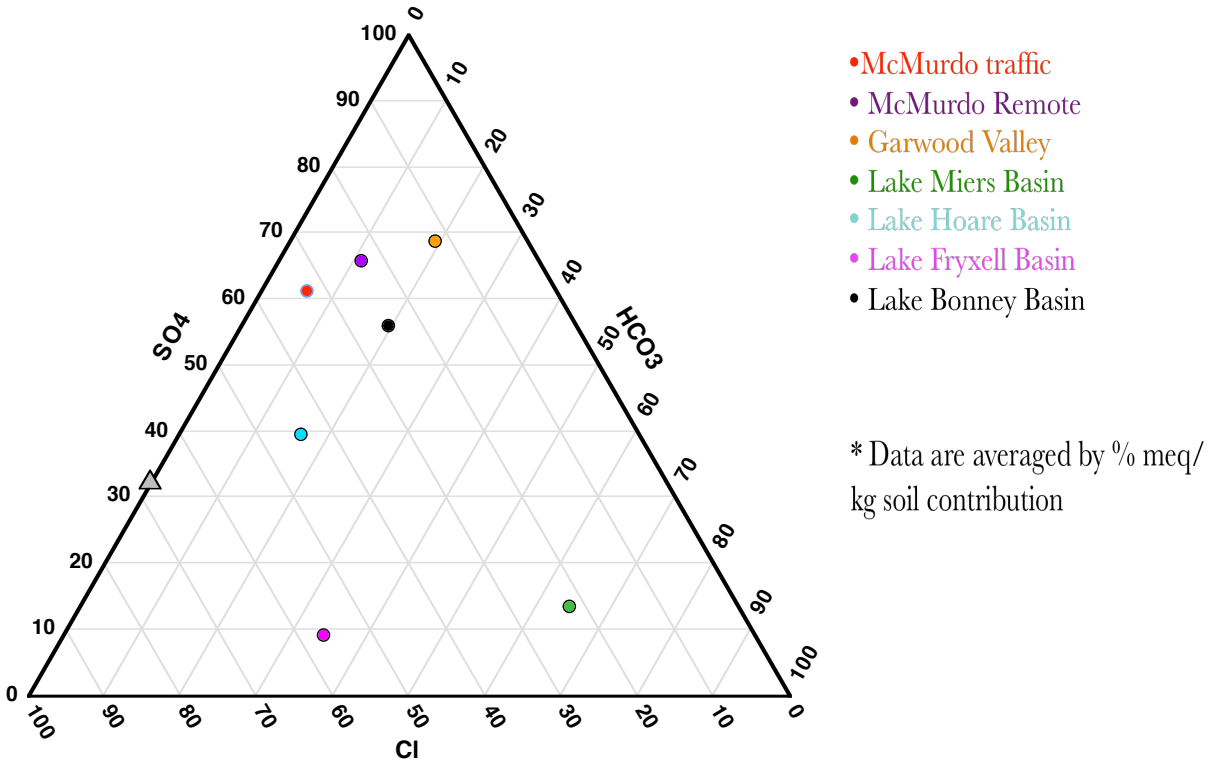

Figure 8. Anion Ternary Diagram with grey triangle representing TV precipitation.

Table 3. Values used for statistical analysis are results of average % ion by AOI.

AOI	avg% Na	avg % K	avg % Mg	avg % Ca	avg % F	avg % Cl	avg % NO3	avg % SO4	avg % HCO3
Close to water	0.87	0.03	0.03	0.07	0.00	0.38	0.01	0.45	0.17
Not close to water	0.89	0.03	0.01	0.07	0.00	0.27	0.01	0.56	0.16
McMurdo high traffic	0.87	0.03	0.02	0.08	0.00	0.24	0.01	0.65	0.09
McMurdo Remote	0.96	0.01	0.00	0.02	0.00	0.30	0.00	0.39	0.30
"Higher" Elevation	0.96	0.01	0.01	0.02	0.00	0.41	0.01	0.29	0.29
Low Elevation	0.87	0.03	0.02	0.07	0.00	0.32	0.01	0.52	0.15
Widespread (streambed)	0.90	0.02	0.01	0.07	0.00	0.28	0.00	0.60	0.11
Isolated (boulder)	0.96	0.02	0.01	0.02	0.00	0.37	0.00	0.25	0.36

Table 4. Table showing results of 2 sample T-Test. Significant differences at the p=.05 level are underlined.

AOI	T-stat Na	T-stat K	T-stat Mg	T-stat Ca	T-stat F	T-stat Cl	T-stat NO3	T-stat SO4	T-stat HCO3	Critical T
Close to water	0.58	-0.55	-0.99	-0.11	0.61	-1.80	1.04	1.14	-0.14	2.11
Not close to water										
McMurdo high traffic	*-5.04*	2.54	*3.38*	*3.95*	1.00	-0.52	1.50	0.00	-1.86	2.57
McMurdo Remote										
"Higher" Elevation	*3.79*	*-3.47*	-1.44	-3.64	0.00	0.73	-0.59	-1.12	1.18	3.18
Low Elevation										
Widespread (streambed)	*2.88*	-0.96	-0.89	-2.69	1.12	0.79	0.03	-1.99	2.11	2.78
Isolated (boulder)										

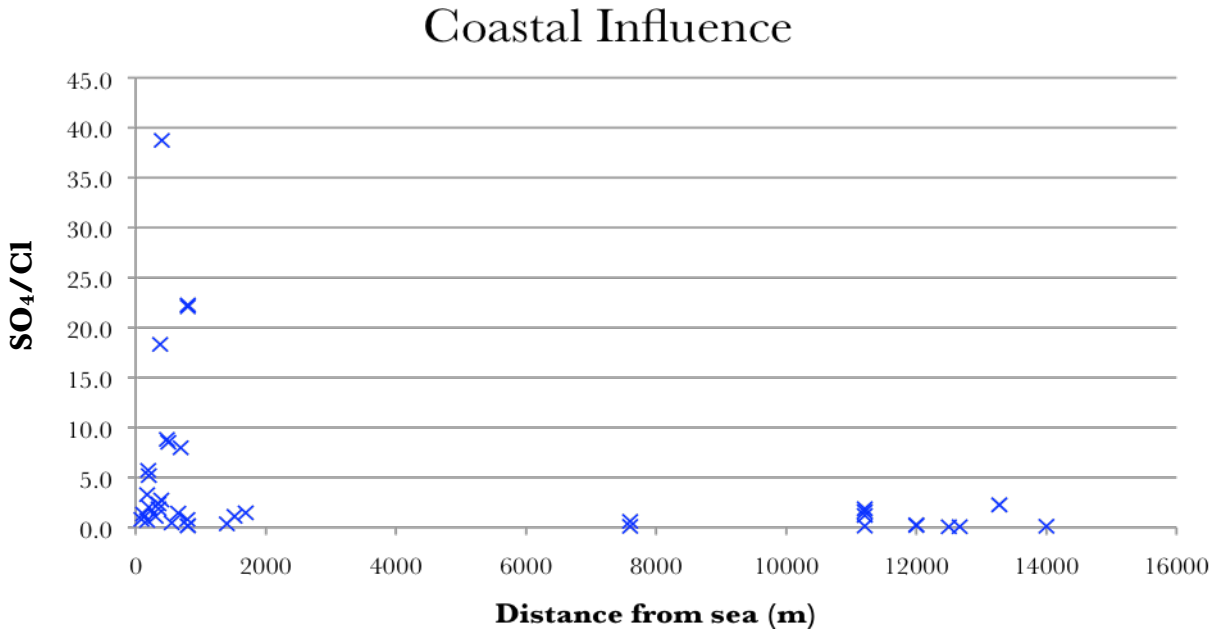

Figure 9. Graph showing SO_4/Cl (by percent ion) plotted against distance from the sea.

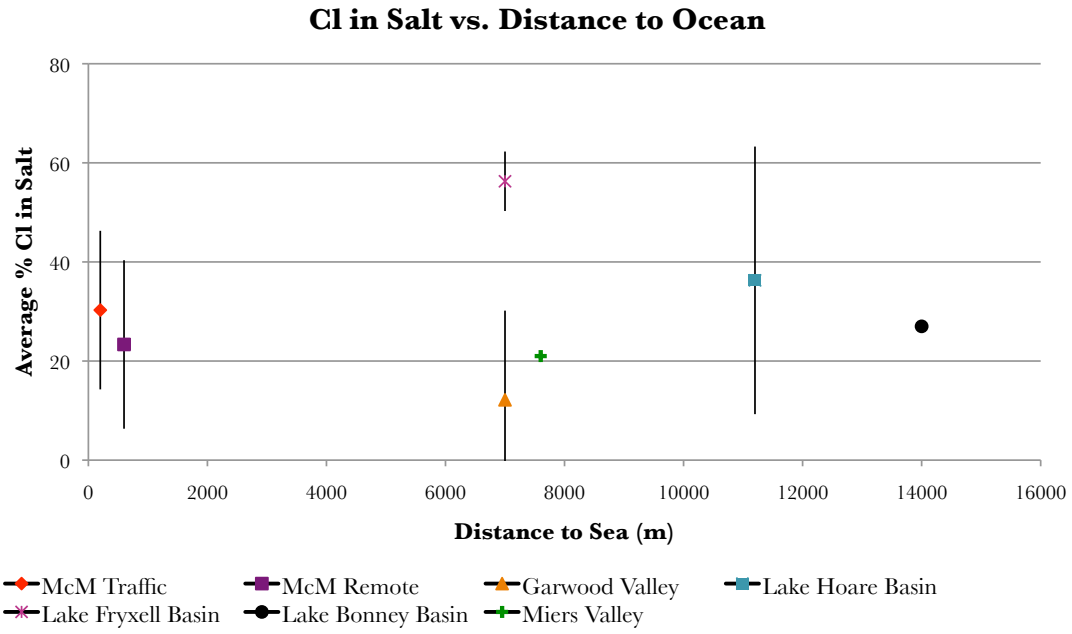

Figure 10. Graph of Cl distribution in salts sampled shows no correlation with distance to the sea.

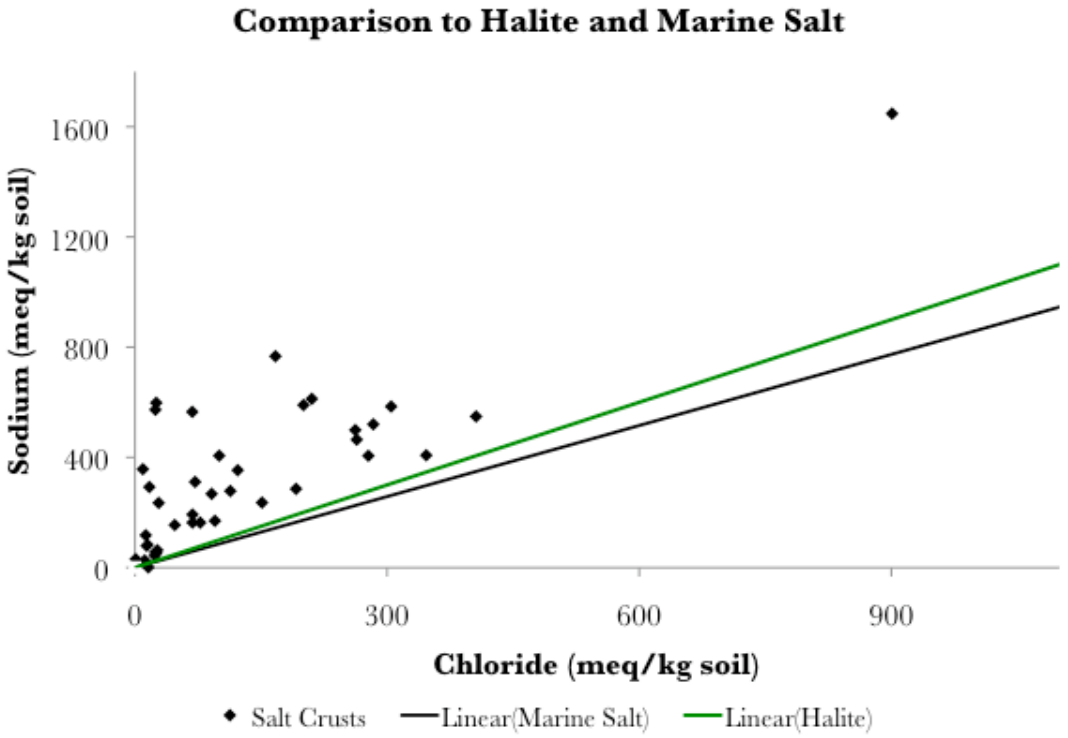

Figure 11. Na/Cl is plotted and all samples show enrichment in Na with respect to halite and marine salt.

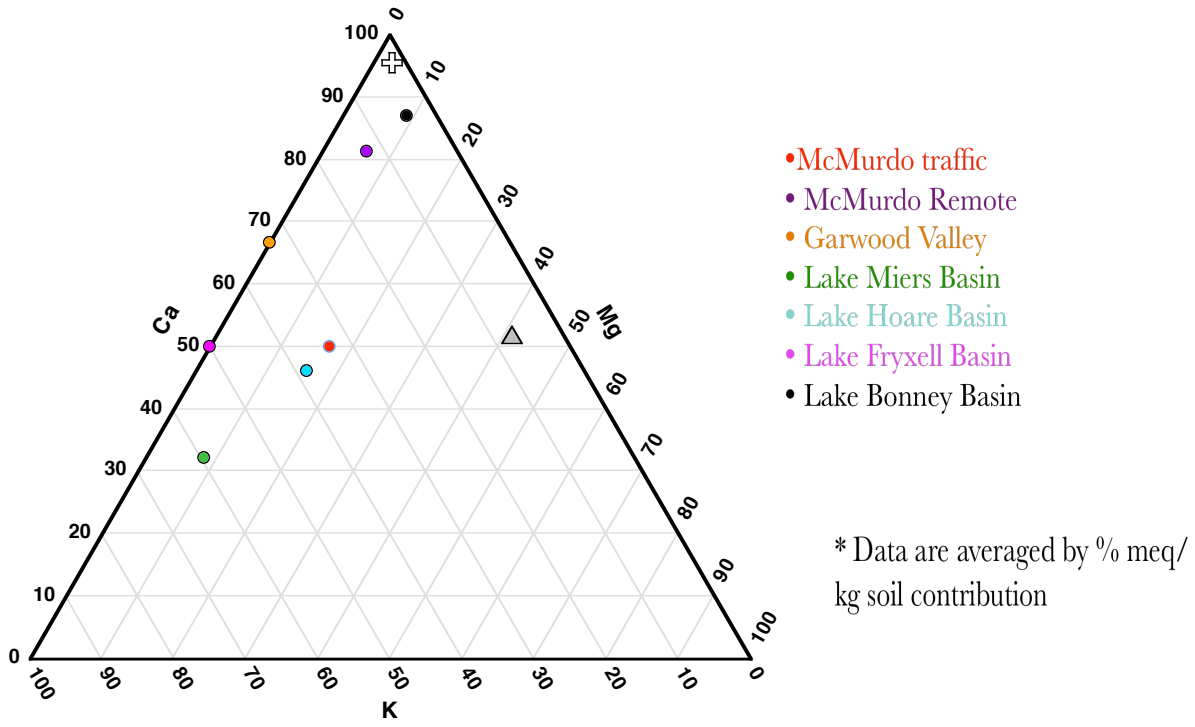

Figure 12. Cation plot without sodium as a constituent shows the variability in the existing cations. The grey triangle represents average Taylor Valley precipitation and the cross represents McMurdo precipitation from one snow sample.

Figure 13. Various photos selected to show sample site variability. A. Base of Castle Rock, West side by approach. Salts form underside of rock face. B. Crary Truck Area. Salt forms near areas of high human traffic and activity. C. Salts form alongside Green Creek, in the hyporheic zone. D. Widespread salts on western side of Observation Hill, roughly 30m from Ross Sea.

Figure 14. Qualitative stoichiometric comparisons show that salts are dominated by sodium as the cation with more variability in the anions.